GEOPHYSICAL RESEARCH LETTERS, VOL. 20, NO. 16, PAGES 1691-1694, AUGUST 20, 1993

W PHASE

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Abstract. The recent Nicaragua tsunami earthquake (September 2, 1992) produced a distinct ramp-like long-period (up to 1000 sec) phase which begins between *P* and *S* waves on displacement seismograms. In terms of ray theory, this phase consists of long-period *P, PP, S, SS, SP, PS*, etc and its propagation mechanism is similar to that of a whispering gallery. In terms of normal-mode theory, it represents a group of higher-mode Rayleigh waves with a group velocity close to, but slower than, that of *P* wave. This phase has not been recognized as a distinct phase in the seismological practice because of clipping of seismograms for very large earthquakes. With the advent of modern wide-dynamic range seismographs, this phase can be easily identified for all large earthquakes. In view of its use for identifying slow earthquakes, determining whether slow deformation is precursory or coseismic to the regular short-period energy release, and determining velocity structures between the source and the station, we propose that this phase be called the "*W* phase".

Typical seismograms exhibit distinct short-period (up to 30 sec) body-wave phases, such as *P, PP, S, SS, SP, PS*, etc, which are followed by longer period (typically 10 to 250 sec) surface waves. Since both body and surface waves originate from the same source, the body-wave part of the seismogram must also contain long-period energy. However, because of the combined effect of seismic source spectrum of ordinary dislocation sources and the conventional instrument response, the long-period wave is usually not visible in the body-wave part of the seismogram and has been seldom used for research. Here, we use the term "body wave" to refer to the phase that arrives before the regular surface waves.

To extract very long-period body waves from a seismogram, short-period waves which dominate the record must be filtered out. Unfortunately, this was not possible until recently because of clipping of records for large earthquakes. With the advent of digital wide-dynamic range instruments, now it is possible to obtain on-scale recordings of large earthquakes, which allows seismologists to use very long-period body waves for studying seismic sources and Earth's structure. A distinct merit of using body waves for source studies is that the propagation path is shorter and simpler than for surface waves so that the source characteristics can be recovered from the observed record easily. This is especially advantageous for determination of the time history of earthquakes. For instance, whether slow seismic deformation precedes or follows the onset of a regular seismic event has been a matter of great interest and debate. In the traditional source studies, long-period surface waves (multiple-circuit Rayleigh and Love waves) and normal-mode data with very long propagation paths were used to determine the initial source phase from which the source time history is determined. This procedure, however, requires very accurate knowledge about the three-dimensional structure of Earth.

A difficulty in using very long-period body waves, however, is that as the period increases and becomes comparable to, or longer than, the time differences between various body-wave phases such as *P, PP, S, SS, PS, SP*, etc, these phases interfere in a complex fashion and cannot be identified as distinct phases. At long period, these phases interfere with each other to produce a distinct long-period phase. Here we call this long-period phase the "*W* phase". *W* phase can be identified easily for large earthquakes, and can be used effectively for studies of long-period source characteristics and regional Earth structure.

The recent slow tsunami earthquake which occurred in Nicaragua on September 2, 1992, produced a clear *W* phase, because of its anomalously long-period character of the source [Kanamori and Kikuchi, 1993]. The source preferentially excited very long-period waves so that *W* phase was clearly visible on displacement seismograms at many stations. Figure 1a shows the displacement record of the Nicaragua earthquake recorded at Pasadena. For comparison, the record of an ordinary earthquake (April 25, 1992 Cape Mendocino,

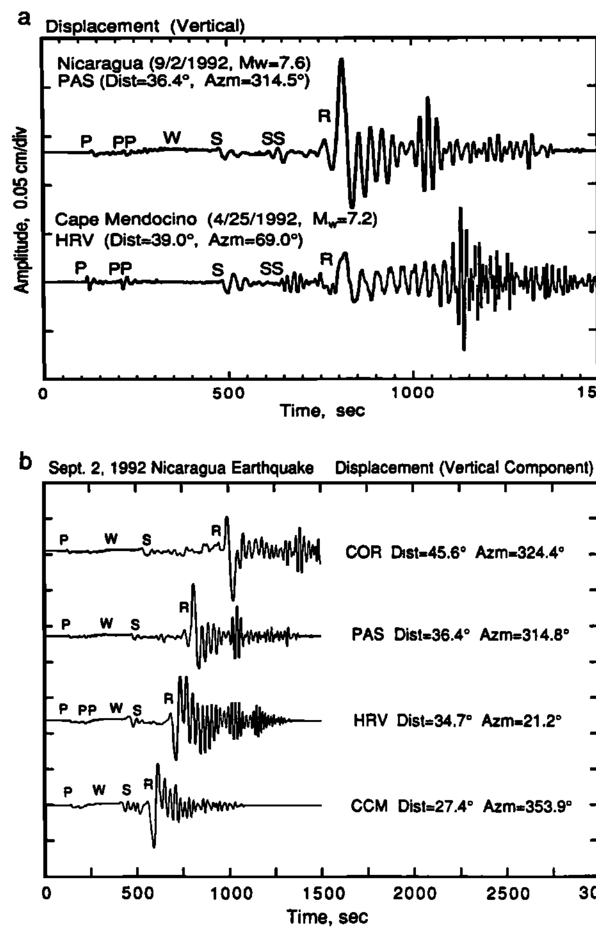

Fig.1. *W* phase observed for the September 2, 1992, Nicaragua earthquake. Figure 1a compares the Nicaragua earthquake with the Cape Mendocino earthquake. Figure 1b shows the seismograms of the Nicaragua earthquake recorded at stations COR, PAS, HRV, and CCM. All the seismograms show displacement computed from the original broadband seismograms.

Paper number 93GL01883
0094-8534/93/93GL-01883$03.00

California, earthquake) is also shown. The long-period *W* phase is evident on the Nicaragua earthquake seismogram. Figure 1b shows the Nicaragua earthquake seismograms recorded at several stations. The *W* phase is distinct at all the stations.

In terms of ray theory, *W* phase can be interpreted as a result of complex interference of many long-period body phases. As shown in Figure 1, it arrives between *P* and *S*, and very often appears to begin after *PP* phase. This latter behavior suggests that *W* phase is primarily a result of superposition of multiply reflected body waves such as *PP*, *SP*, *PS* etc. In a way, this mode of propagation is analogous

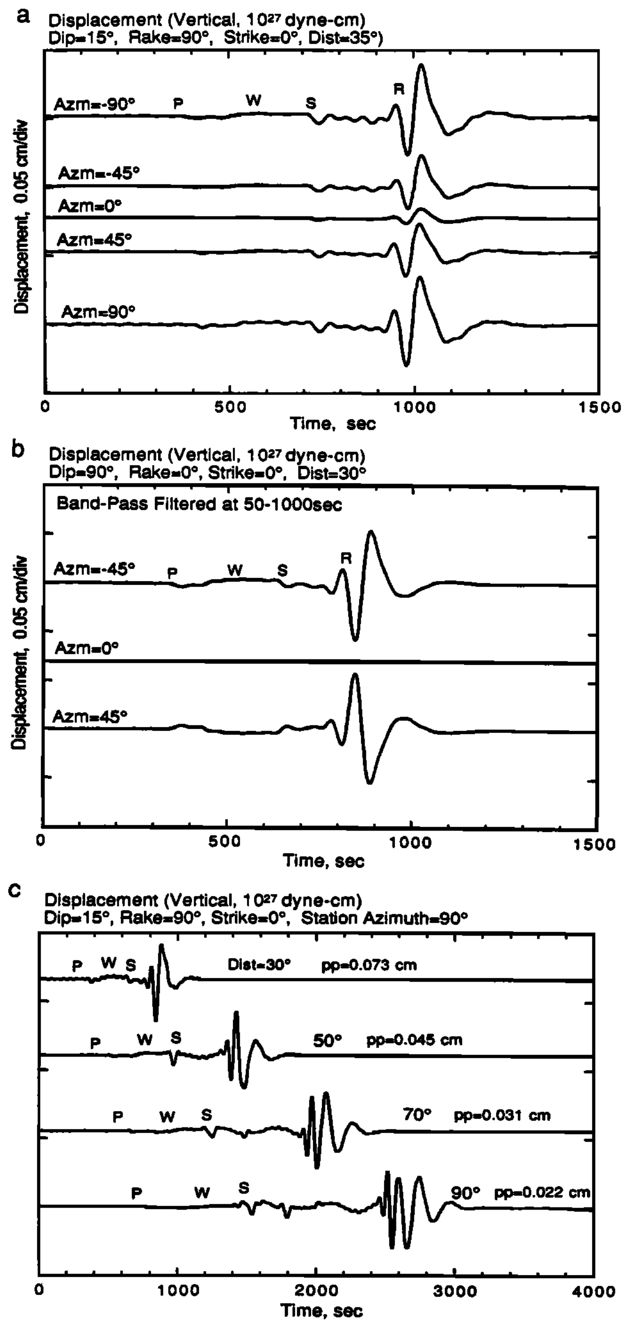

Fig.2. Synthetic seismograms of *W* phase computed by superposition of normal modes. a. The azimuthal variation of *W* phase for a thrust mechanism. b. The azimuthal variation of *W* phase for a strike-slip mechanism. c. The variation of *W* phase as a function of distance for a thrust mechanism.

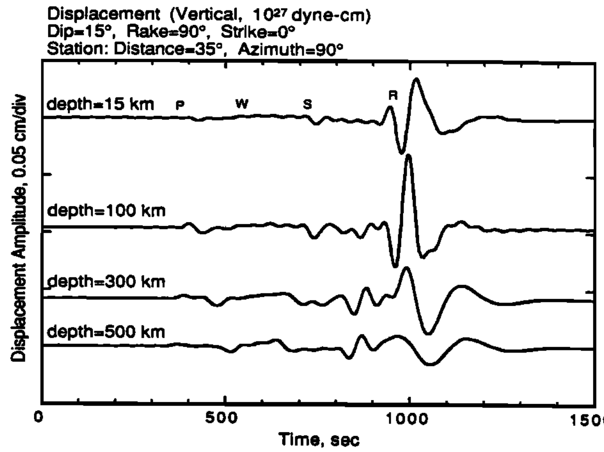

Fig.3. The variation of *W* phase with depth for a thrust mechanism with a dip angle of 15°.

to that of a whispering gallery [Rayleigh, 1896, page 126; Sato, 1961] in acoustics. Because of the *S* to *P* and *P* to *S* conversions in elastic media, however, propagation mechanism of *W* phase is more complex than that of a whispering gallery. Nevertheless, because of this analogy, we call this long-period phase the "*W* phase". Useful accounts of whispering-gallery type wave propagation in Earth's interior

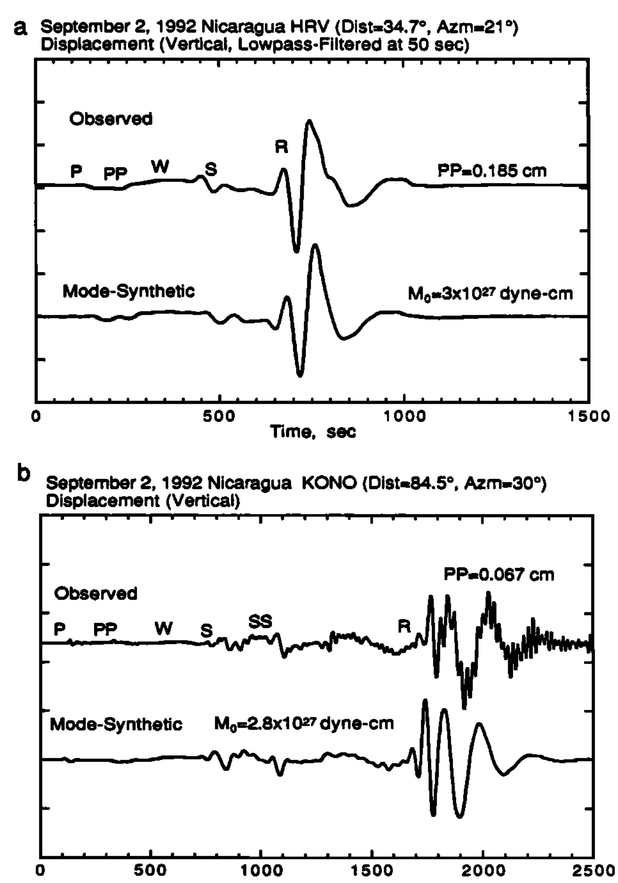

Fig.4. Comparison of the synthetic and observed records for the Nicaragua earthquake for stations HRV (a) and KONO (b). The mechanism determined by Kanamori and Kikuchi [1993] is used.

can be found in Aki and Richards [1980, page 452-461] and Bullen and Bolt [1985, page 192].

A straightforward way to compute this phase is by normal-mode superposition. Figure 2 shows synthetic seismograms computed by superposition of normal modes for a point source placed at a depth of 15 km. In this synthesis, 3375 spheroidal modes for periods longer than 30 sec computed by Buland [1976] for Earth model 1066 A [Gilbert and Dziewonski, 1975] are used. Although no filter was applied to the synthetics, the cut-off of the mode data at a period of 30 sec in the synthetics effectively filtered out short-period waves. Figures 2a and 2b show the azimuthal variation of the waveforms for a source with thrust and strike-slip mechanisms, respectively. The radiation patterns of *W* phase are in general similar to those of the fundamental-mode Rayleigh wave. Note that the overall motion of *W* phase is always "up" for a thrust mechanism regardless of the azimuth (i.e. "down" for a normal-fault mechanism); it is "up" and "down" in the *P*-wave dilatational and compressional quadrants of a strike-slip mechanism, respectively. This feature is useful for determining the mechanism. Figure 2c shows the variation as a function of distance; *W* phase is most distinct at distances shorter than 50°. At large distances *W* phase becomes a very long-period wave that continues to the fundamental-mode Rayleigh wave. Figure 3 shows the variation of *W* phase as a function of depth. Although the waveform of *W* phase varies considerably as a function of depth, it can be easily identified for both shallow and deep earthquakes.

As shown above, in the context of normal-mode theory *W* phase represents many higher-mode Rayleigh waves that propagate at a group velocity close to, but slower than, that of *P* wave. The depth variation of the waveform, shown in Figure 3, is due to excitation of different higher modes at different depths. Since *W* phase appears as a distinct ramp-like long-period phase on modern seismograms, and is useful for studies of long-period source characteristics, we feel that it is desirable to give it a name.

Figure 4 shows examples for the Nicaragua earthquake. As shown in Figure 4a, for the station HRV (Harvard Massachusetts) which is located near the radiation pattern maximum of Rayleigh wave, both *W* phase and Rayleigh wave can be synthetically reproduced very well. For the station KONO (Figure 4b) which is located at a distance of 84.5°, *W* phase is not separated from the Rayleigh wave, but its beginning before the *S* phase is still distinct.

W phase should be expected for any earthquakes, but for ordinary earthquakes, it is masked by short period waves, which has prevented it from being identified in routine seismological practice. To demonstrate how ubiquitous it is we show displacement records of several large earthquakes in Figure 5. The original unfiltered seismograms and band-pass filtered (70-1000 sec) seismograms are shown in Figures 5a to 5d. *W* phase is recognizable on the unfiltered record for the Flores Is. earthquake and the Mindanao Is. earthquake, but not for the Cape Mendocino and the Shumagin Is. earthquakes. The band-pass filtered seismograms clearly exhibit *W* phase for all the earthquakes.

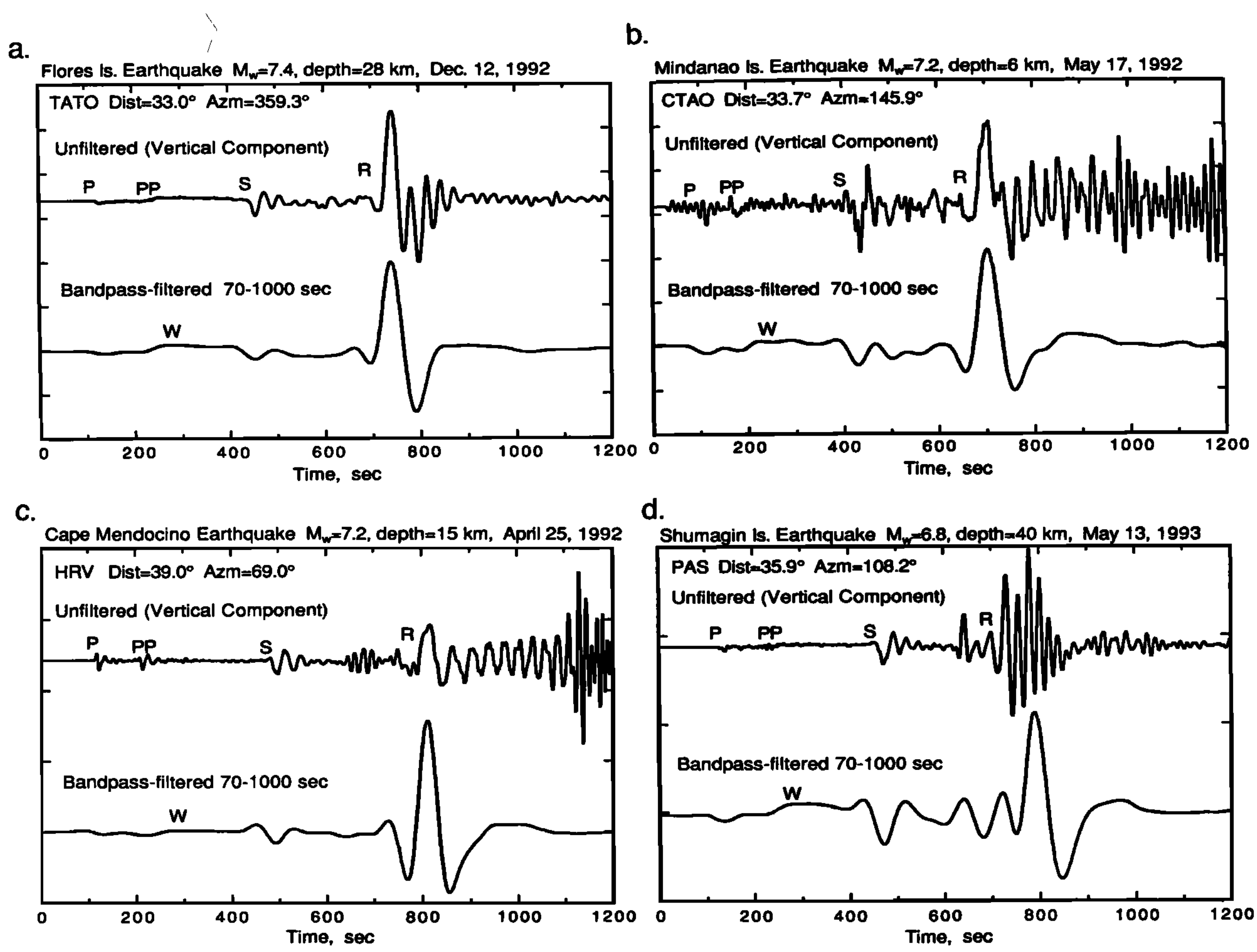

Fig.5. Examples of *W* phase. The records on top are the unfiltered seismograms and those on bottom, bandpass-filtered. a. Flores Is. earthquake. b. Mindanao Is. earthquake. c. Cape Mendocino earthquake. d. Shumagin Is. earthquake.

Since *W* phase is mainly sensitive to the velocity structure in the upper mantle between the source and the station, detailed studies of *W* phase would provide useful information about the regional variations of velocity structure. *W* phase can be also used effectively for seismological tsunami warning system, because it arrives early and is diagnostic of tsunami potential of the event.

Acknowledgments. The name "*W* phase" is suggested by Don Anderson. This research was partially supported by the U. S. Geological Survey Grant 1434-93-G2305. This research was conducted under the TERRAscope project supported by the L. K. Whittier and Arco Foundations. Contribution No. 5286, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125.

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(Received June 9, 1993;
accepted July 8, 1993)